Mg IX EMISSION LINES IN AN ACTIVE REGION SPECTRUM OBTAINED WITH THE SOLAR EUV ROCKET TELESCOPE AND SPECTROGRAPH (SERTS)

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Abstract. Theoretical electron-temperature-sensitive Mg IX emission line ratios are presented for $R_1 = I(443.96 \text{ Å})/I(368.06 \text{ Å})$, $R_2 = I(439.17 \text{ Å})/I(368.06 \text{ Å})$, $R_3 = I(443.37 \text{ Å})/I(368.06 \text{ Å})$, $R_4 = I(441.22 \text{ Å})/I(368.06 \text{ Å})$, and $R_5 = I(448.28 \text{ Å})/I(368.06 \text{ Å})$. A comparison of these with observational data for a solar active region, obtained during a rocket flight by the Solar EUV Rocket Telescope and Spectrograph (SERTS), reveals excellent agreement between theory and observation for R_1 through R_4, with discrepancies that average only 9%. This provides experimental support for the accuracy of the atomic data adopted in the line ratio calculations, and also resolves discrepancies found previously when the theoretical results were compared with solar data from the S082A instrument on board *Skylab*. However in the case of R_5, the theoretical and observed ratios differ by almost a factor of 2. This may be due to the measured intensity of the 448.28 Å line being seriously affected by instrumental effects, as it lies very close to the long wavelength edge of the SERTS spectral coverage (235.46–448.76 Å).

1. Introduction

Numerous emission lines arising from transitions among the $2s^2$, $2s2p$, and $2p^2$ levels of ions in the beryllium isoelectronic sequence have been detected in solar ultraviolet spectra (Widing, Feldman, and Bhatia, 1986; Vernazza and Reeves, 1978; Sandlin *et al.*, 1986). These transitions may be used to determine the electron temperature and/or density of the solar transition region and corona through diagnostic line ratios, although to calculate these reliably, accurate atomic data must be employed, especially for electron impact excitation rates (Dufton and Kingston, 1981). For the last ten years we have been involved in an extensive series of electron temperature and density diagnostic calculations for solar plasmas (see, for example, Keenan and Warren, 1993) using electron excitation rates for Be-like ions either determined with the R-matrix code or interpolated from these (see Keenan, 1988, and references therein).

As part of the above programme, Keenan *et al.* (1992a) recently presented diagnostic line ratios for Mg IX, and compared these with intermediate spectral resolution solar observations from the S082A instrument on board *Skylab*. However some of the observed line ratios were much larger than the theoretical predictions (by up to a factor of 3.2), which was suggested might be due to blending in the S082A data. Similar discrepancies were also found for C IV emission lines observed by the S082A spectrograph (Keenan *et al.*, 1992b), which were resolved by Keenan *et al.* (1993) when the theoretical ratios were compared with higher quality solar observations obtained with the Solar EUV Rocket Telescope and Spectrograph (SERTS). In the present paper we therefore compare the theoretical Mg IX results with SERTS data, to investigate if the discrepancies noted above for this ion can be removed.

2. Theoretical Ratios

The model ion adopted for Mg IX has been discussed in detail by Keenan *et al.* (1992a). Briefly, the six energetically lowest LS states were included in the calculations, namely $2s^2\,{}^1S$; $2s2p\,{}^3P$, ${}^1P$; $2p^2\,{}^3P$, ${}^1D$, and ${}^1S$, making a total of ten levels when the fine structure splitting in the triplet terms is included. Only collisional excitation and de-excitation by electrons and protons (the latter in the case of transitions among $2s2p\,{}^3P$), and spontaneous radiative de-excitation processes were considered, and the plasma was assumed to be optically thin. Further details may be found in Keenan *et al.* (1992a).

In Keenan *et al.* (1992a), the following Mg IX emission line ratios were considered:

$$R_1 = I(2s2p\,{}^3P_2 - 2p^2\,{}^3P_2)/I(2s^2\,{}^1S - 2s2p\,{}^1P) =$$
$$= I(443.96\,\text{Å})/I(368.06\,\text{Å})\,,$$

$$R_2 = I(2s2p\,{}^3P_1 - 2p^2\,{}^3P_2)/I(2s^2\,{}^1S - 2s2p\,{}^1P) =$$
$$= I(439.17\,\text{Å})/I(368.06\,\text{Å})\,,$$

$$R_3 = I(2s2p\,{}^3P_1 - 2p^2\,{}^3P_1)/I(2s^2\,{}^1S - 2s2p\,{}^1P) =$$
$$= I(443.37\,\text{Å})/I(368.06\,\text{Å})\,,$$

and

$$R_4 = I(2s2p\,{}^3P_0 - 2p^2\,{}^3P_1)/I(2s^2\,{}^1S - 2s2p\,{}^1P) =$$
$$= I(441.22\,\text{Å})/I(368.06\,\text{Å})\,.$$

These ratios are sensitive to variations in the electron temperature, as the upper levels of the relevant transitions ($2p^2\,{}^3P$ and $2s2p\,{}^1P$) are well separated in energy

(see Keenan, 1992). However for values of $N_e \geq 10^{11.5}$ cm^{-3}, R_1 through R_4 are both T_e- and N_e-sensitive, the density dependence being due to the movement of the $2s2p\ ^3P$ level populations towards Boltzmann equilibrium. As Keenan *et al.* (1992a) were primarily concerned with the analysis of a very high density solar flare (1973 December 2 at 15:17 UT), for which $\log N_e \simeq 12.5$ (see Feldman and Widing, 1990), they plotted R_1 through R_4 as a function of electron density, and used the ratios as density diagnostics. The temperature sensitivity of R_1 through R_4 did not seriously affect the results of Keenan *et al.*, as at $\log N_e \simeq 12.5$ a change of $\sim 50\%$ in the adopted T_e leads to a ≤ 0.3 dex variation in the derived density (see Figures 1–4 of Keenan *et al.*, 1992a).

We note that under nearly all solar conditions (including the active region observations considered in this paper), the electron density will be less than $10^{11.5}$ cm^{-3}, and R_1 through R_4 will therefore be independent of N_e. Hence they are plotted in Figures 1 and 2 at an electron density of $N_e = 10^{10}$ cm^{-3} for the range of electron temperatures over which the fractional abundance of Mg IX ionization equilibrium is $\geq 10^{-3}$ (Arnaud and Rothenflug, 1985). Also plotted in Figure 2 is a ratio not considered by Keenan *et al.* (1992a), namely

$$R_5 = I(2s2p\ ^3P_2 - 2p^2\ ^3P_1)/I(2s^2\ ^1S - 2s2p\ ^1P) =$$
$$= I(448.28\ \text{Å})/I(368.06\ \text{Å})\ .$$

An inspection of Figures 1 and 2 reveals that R_1 through R_5 are quite sensitive to changes in the electron temperature, and are hence potentially very useful T_e-diagnostics for all but the highest density solar features. For example, R_1 varies by a factor of 2.1 between $\log T_e = 5.7$ and 6.4, while R_3 changes by a factor of 2.0 over the same temperature interval. We note in passing that the temperature sensitivity of the ratios is similar at high values of electron density ($\geq 10^{11.5}$ cm^{-3}), when they also become N_e-sensitive.

3. Observational Data

The solar spectrum analysed in the present paper was that of active region NOAA 5464, including emission from the early stages of a subflare. The spectrum was recorded on Eastman Kodak 101-07 emulsion by the Solar EUV Rocket Telescope and Spectrograph (SERTS) during a rocket flight on 1989 May 5 at 17:50 UT. This instrument covered the wavelength region 235.46–448.76 Å in first order, with a spatial resolution of about 7 arc sec and a spectral resolution of better than 80 mÅ (FWHM). It is discussed in detail by Neupert *et al.* (1992). The observations used here have been spatially averaged over the central 4.6 arc min of the spectrograph slit, and converted to absolute intensities by procedures described in Thomas and Neupert (1993).

We have identified the following Mg IX emission lines in the SERTS spectrum: 368.06 Å $(2s^2\ ^1S - 2s2p\ ^1P)$, 439.17 Å $(2s2p\ ^3P_1 - 2p^2\ ^3P_2)$, 441.22 Å $(2s2p\ ^3P_0 -$
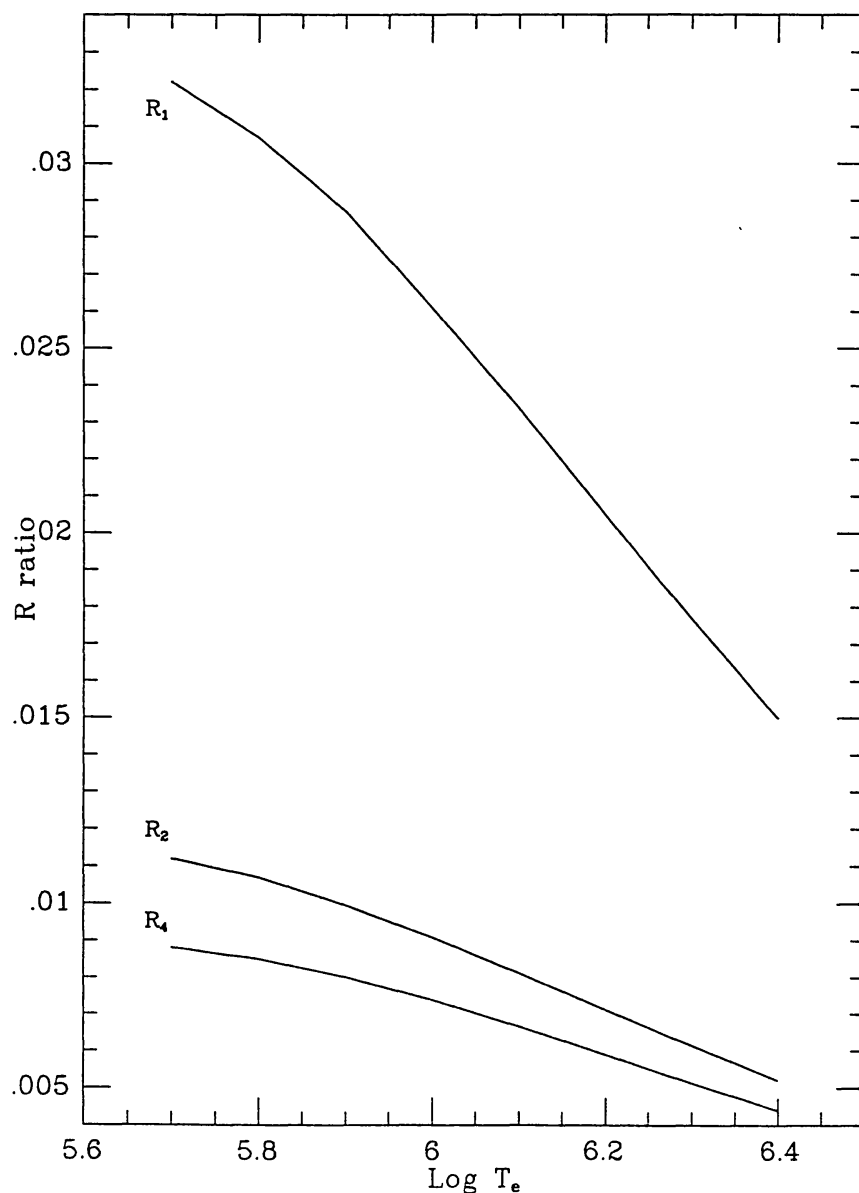
Fig. 1. The theoretical Mg IX emission line ratios

$R_1 = I(2s2p\,^3P_2 - 2p^2\,^3P_2)/I(2s^2\,^1S - 2s2p\,^1P) = I(443.96\ \text{Å})/I(368.06\ \text{Å})$,

$R_2 = I(2s2p\,^3P_1 - 2p^2\,^3P_2)/I(2s^2\,^1S - 2s2p\,^1P) = I(439.17\ \text{Å})/I(368.06\ \text{Å})$,

and

$R_4 = I(2s2p\,^3P_0 - 2p^2\,^3P_1)/I(2s^2\,^1S - 2s2p\,^1P) = I(441.22\ \text{Å})/I(368.06\ \text{Å})$,

where I is in energy units, plotted as a function of electron temperature at an electron density of $N_e = 10^{10}\ \text{cm}^{-3}$.

$2p^2\,^3P_1$), 443.37 Å $(2s2p\,^3P_1 - 2p^2\,^3P_1)$, 443.96 Å $(2s2p\,^3P_2 - 2p^2\,^3P_2)$, and 448.28 Å $(2s2p\,^3P_2 - 2p^2\,^3P_1)$. The intensities of these lines were determined by fitting gaussian profiles to microdensitometer scans of the recorded spectrum. The intensity of the 368.06 Å line is listed in Table I; the observed intensities of the
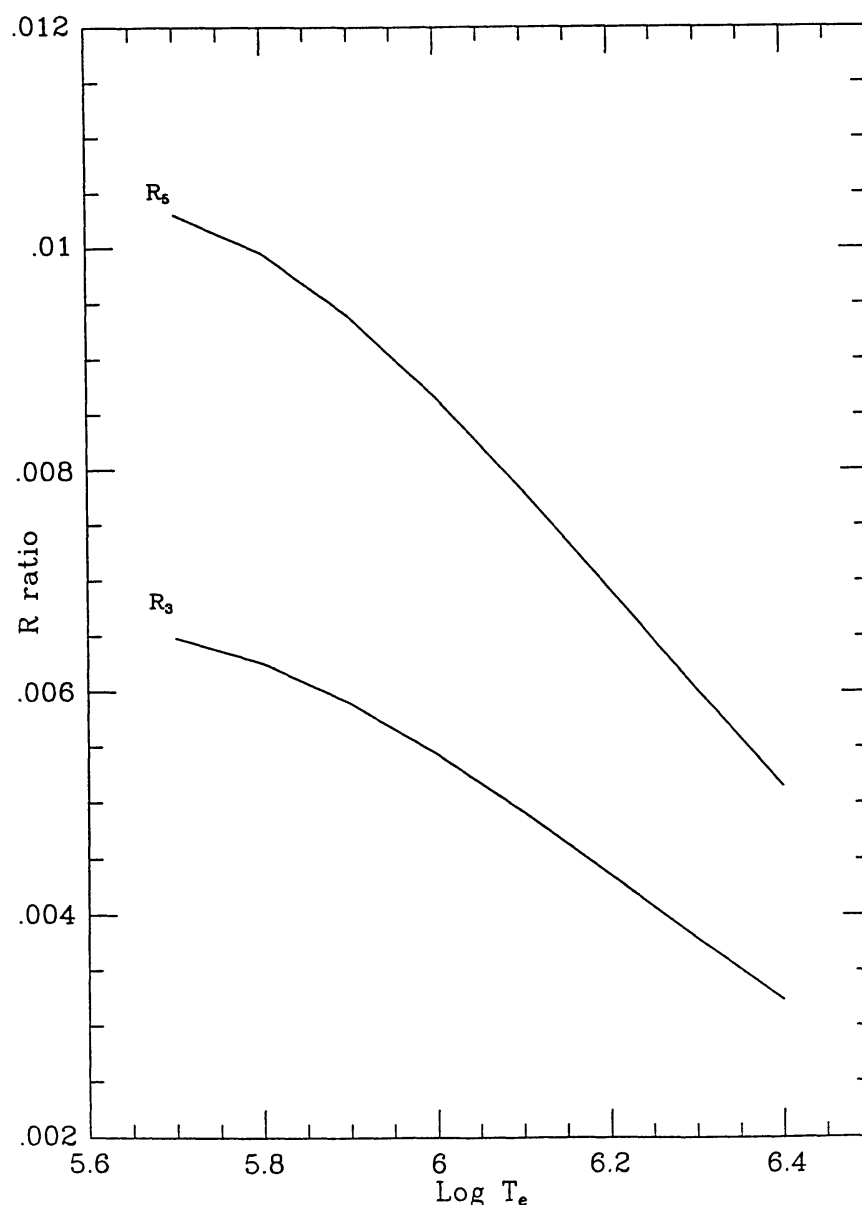
Fig. 2. The theoretical Mg IX emission line ratios

$$R_3 = I(2s2p\,^3P_1 - 2p^2\,^3P_1)/I(2s^2\,^1S - 2s2p\,^1P) = I(443.37\ \text{Å})/I(368.06\ \text{Å})$$

and

$$R_5 = I(2s2p\,^3P_2 - 2p^2\,^3P_1)/I(2s^2\,^1S - 2s2p\,^1P) = I(448.28\ \text{Å})/I(368.06\ \text{Å}),$$

where I is in energy units, plotted as a function of electron temperature at an electron density of $N_e = 10^{10}\ \text{cm}^{-3}$.

other Mg IX transitions may be inferred from this using the line ratios quoted in Table I (see Section 4).

The quality of the observational data are illustrated in Figures 3 and 4, where we plot the active region spectrum between 367.8–368.4 Å and 443.2–444.2 Å, respectively.
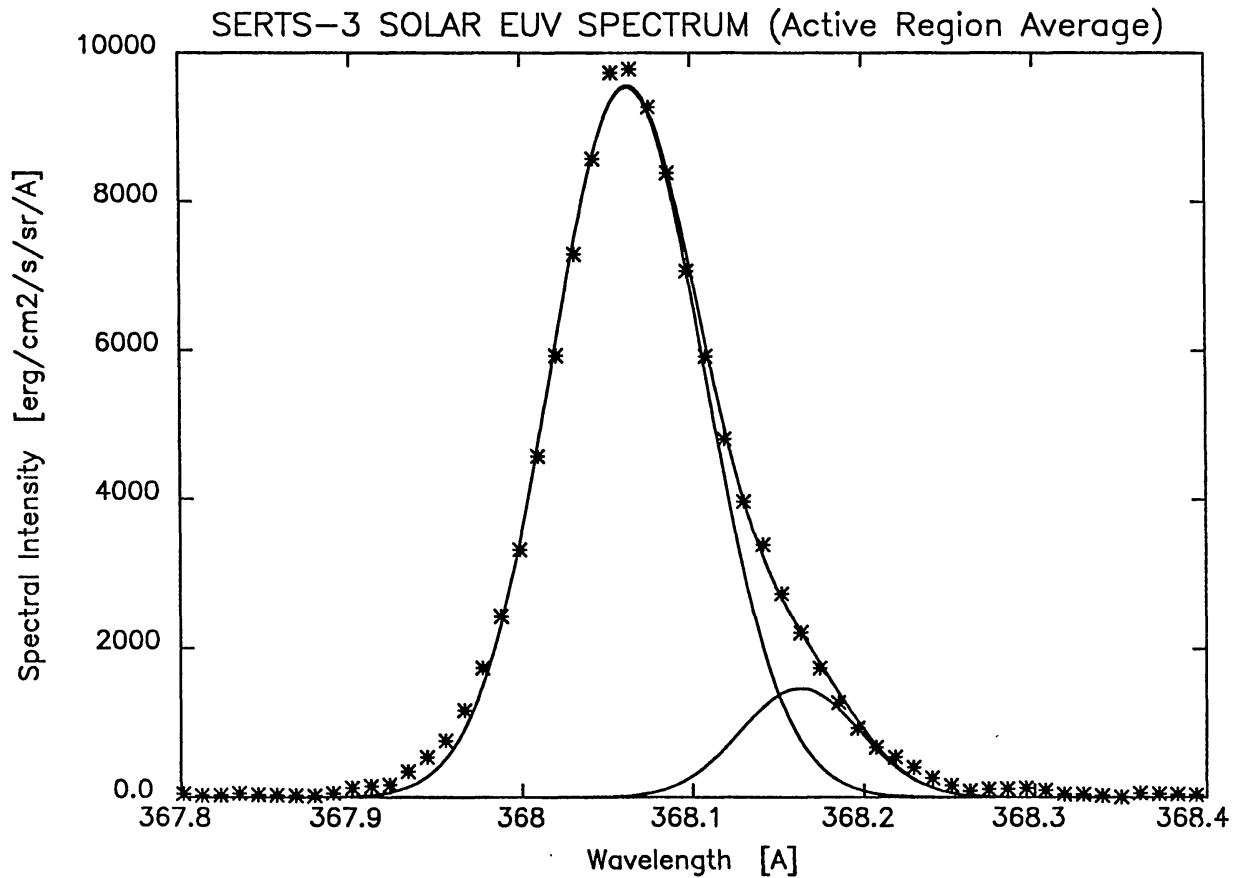
Fig. 3. Plot of the active region spectrum obtained with SERTS in the wavelength interval 367.8–368.4 Å. Gaussian fits to the Mg IX 368.06 Å line and to the Cr XIII/Fe XIII blend at 368.16 Å are shown.

TABLE I

Observed and theoretical Mg IX emission line ratios

λ (Å)	$R_{obs} = I(\lambda)/I(368.06 \text{ Å})$[a]	R_{theory}[b]
443.96	$1.90 - 2$ (R_1)[c]	$2.61 - 2$
439.17	$8.79 - 3$ (R_2)	$9.09 - 3$
443.37	$5.23 - 3$ (R_3)	$5.43 - 3$
441.22	$7.20 - 3$ (R_4)	$7.39 - 3$
448.28	$4.77 - 3$ (R_5)	$8.65 - 3$

[a] $I(368.06\text{Å}) = 1070 \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$.

[b] Calculated at the electron temperature of maximum Mg IX fractional abundance in ionization equilibrium, $\log T_e = \log T_{max} = 6.0$ (Arnaud and Rothenflug, 1985).

[c] $A - B$ implies $A \times 10^{-B}$.

4. Results and Discussion

In Table I we list the observed emission line ratios R_1 through R_5 along with the theoretical results from Figures 1 and 2 at the electron temperature of maximum
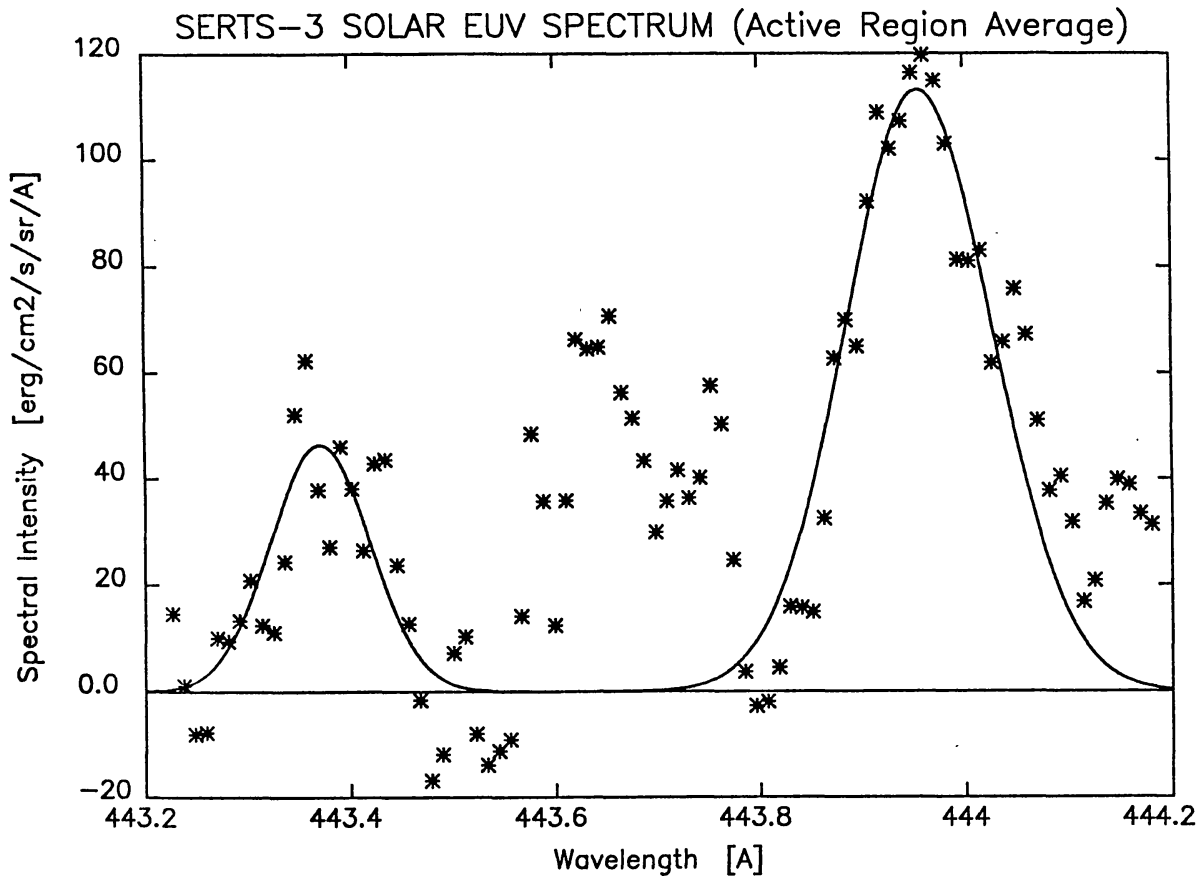
Fig. 4. Plot of the active region spectrum obtained with SERTS in the wavelength interval 443.2–444.2 Å. Gaussian fits to the Mg IX 443.37 Å and 443.96 Å lines are shown. Between them is a feature identified as Fe XIII 221.83 Å observed in second order.

Mg IX fractional abundance in ionization equilibrium, $\log T_e = \log T_{max} = 6.0$ (Arnaud and Rothenflug, 1985). An inspection of the table reveals excellent agreement between theory and observation for R_1 through R_4, with discrepancies that do not exceed $\sim 25\%$ and average only 9%, which is well within the observational uncertainty in the line ratios ($\sim 30\%$). As both the $2s^2\ ^1S - 2s2p\ ^1P$ resonance line and the $2s2p\ ^3P_J - 2p^2\ ^3P_{J'}$ transitions have large A-values, they are in the coronal approximation (Elwert, 1952), and hence the values of R_1 through R_4 depend principally on the ratio of the $2s^2\ ^1S - 2s2p\ ^1P$ and $2s2p\ ^3P_J - 2p^2\ ^3P_{J'}$ electron impact excitation rates. The good agreement between theory and observation for R_1 through R_4 therefore provides experimental support for the accuracy of the adopted atomic data. In addition, the present results resolve the serious discrepancy between theory and *Skylab* S082A observations found by Keenan *et al.* (1992a) for R_3 and R_4. Keenan *et al.* (1992a) suggested that these discrepancies are due to the Mg IX 443.37 and 441.22 Å lines being blended with Ar IV 443.44 Å and Mg VI/Mg VII 441.22 Å, respectively. However our analysis indicates that these species contribute little to the observed 443.37 and 441.22 Å line intensities, at least in non-flaring solar features. On the other hand, SERTS data do show that

there is a feature at 368.16 Å (seen in Figure 3 and identified as a blend of Cr XIII and Fe XIII), which would not have been resolved in the *Skylab* measurements of Mg IX 368.06 Å. Emission from the Cr XIII/Fe XIII feature would have affected all of the ratios considered by Keenan *et al.* (1992a), although probably not by large amounts.

Finally, in the case of R_5, the discrepancy between the observed and theoretical line ratios is almost a factor of 2 (see Table I). However we note that the 448.28 Å line lies very close to the long wavelength cutoff of the SERTS spectral coverage (448.76 Å), and its measured intensity may therefore be seriously affected by instrumental effects, such as partial vignetting from the edge of the film aperture mask (Thomas and Neupert, 1993). Further observations of Mg IX (perhaps with the Coronal Diagnostic Spectrometer on board SOHO; Harrison, 1993) would be of great interest to investigate if the discrepancy between theory and observation for R_5 could be removed.

Acknowledgements

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